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THIN FILM OPTICAL WAVEGUIDES IN III-V SEMICONDUCTORS

M. George Craford

Monsanto Company

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800 N. Lindbergh Boulevard
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13. ABSTRACT

A number of GaAs/GaAsP waveguides have been grown on wafers with maximum dimensions on the order of 7 cm. The surface alloy composition variation is within less than 1%. Waveguide attenuation measurement at 10.6 μm gives a 2 dB/cm loss for a single mode waveguide, which is the lowest reported to date. Freliminary result on sandwiched GaAsP/GaAs/GaAsP gives a 6 dB/cm loss for a single mode waveguide. Waveguide work at one micron wavelength has been initiated. Light couplings through edge illumination, grating coupler, and prism coupler are successful.

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14. KEY WORDS	LINK A		LINK B		LINK C	
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Gallium arsenide phosphide						
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Integrated optics						
Thin film waveguides						
Electro-optical modulation						
Optical attenuation						

FOREWORD

This semi-annual technical report covers the work performed under contract F19628-72-C-0324 between the period of January 1, 1974, to June 30, 1974.

The objective of this program is to grow a variety of epitaxial GaAs, GaAsP and GaAlAs waveguide structures and to evaluate their performance with regard to the propagation of 10.6μm radiation. The effect of such parameters as layer thickness, alloy composition profile, and carrier concentration will be investigated. Vapor phase epitaxial techniques are being employed to grow the GaAsP structures and liquid phase epitaxial techniques have been used to grow the GaAlAs structures. During this reporting period, waveguide evaluation at one micron wavelength has been initiated.

Technical direction is being provided by Dr. Andrew Yang of the Air Force Cambridge Research Laboratory. The growth of the epitaxial structures is being carried out in the Monsanto Commerical Products Company, Electronic Products Division, Laboratories, St. Louis, Missouri, and the waveguide evaluation has been subcontracted to and is being performed in the laboratories of the Washington University School of Engineering and Applied Science, St. Louis, Missouri.

The research carried out in this program is under the direction of M. George Craford. Others directly involved in this work and in the preparation of this report are D. Finn, W. O. Groves, of Monsanto Company, and W. S. C. Chang, M. W. Muller, and M. S. Chang, of Washington University.

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1. SUMMARY OF RESULTS

The following results have been obtained during this reporting period:

- GaAs/GaAsP waveguides have been successfully grown on wafers with maximum dimensions on the order of 7 cm.
- The GaAsP layer has a surface alloy composition variation to within less than 1%.
- A single-mode GaAs/GaAsP waveguide has an attenuation rate of 2 dB/cm at 10.6 μm. This is the lowest reported to date.
- A GaAs/AlGaAs waveguide has an attenuation rate of 3 dB/cm for TE_0 mode, 5 dB/cm for TE_1 mode at 10.6 μm.
- The refractive index of $GaAs_{1-x}P_x$ at 10.6 μm has been estimated with a depression $\Delta n = -0.4X$.
- Waveguide work at one micron wavelength (i.e., 1.06 μm and 1.15 μm) has been initiated. Light couplings through edge illumination, grating coupler, and prism coupler are successful.
- A thin-film dye laser has been successfully coupled into a glass waveguide through the block coupling mechanism. This demonstrates the feasibility to couple in $In_xGa_{1-x}As$ laser at 1.06 μm into our GaAs/GaAsP waveguide.
- Two written papers have been accepted for publication: "Low-Loss Two-Dimensional GaAs Epitaxial Waveguides at 10.6 μm Wavelength", IEEE Transaction on Microwave and Theory and Techniques, Vol. MTT-22, June, 1974. Also, "Low-Loss Large-Area GaAs/GaAsP Heterostructure as Optical Waveguide at 10.6 μm", Optics Communications, Vol. 11, pp. 201-203, June, 1974.

- Two contributed papers were presented at the DOD/Industry-Wide Integrated Optics and Fiber Optics Communications Conference, San Diego, 15-17 May, 1974: "Low-Loss Large-Area GaAs/GaAsP Heterostructure as Optical Waveguide at 10.6 μm"; "The Block Coupler - A Hybrid Approach to Integrated Optics".

2. VAPOR PHASE EPITAXY

2.1 Introduction

The objectives of the Vapor Phase Epitaxy portion of this program are to grow various $GaAs/GaAs_{1-x}P_x$ and $GaAs_{1-x}P_x/GaAs/GaAs_{1-x}P_x$ waveguide structures to determine the waveguide properties as functions of film thickness, carrier concentration and alloy composition. Work has been concentrated on $GaAs/GaAs_{1-x}P_x$ structures. Some preliminary work has been done to grow $GaAs_{1-x}P_x/GaAs/GaAs_{1-x}P_x$ structures. Various GaAs film thicknesses are grown for waveguide evaluation at 10.6 μm and 1.06 μm (also 1.15 μm) wavelengths. The need for one-micron integrated optical circuitry arises from the low loss optical fibers at that wavelength. We are capable to do the work simply by growing very thin GaAs films.

2.2 $GaAs/GaAs_{1-x}P_x$ Waveguides

Growth conditions have been developed which produces GaAs/GaAsP structures of good surface quality. The bowing of the large area GaAs/GaAsP structures has been brought under control. Various GaAs film thicknesses have been grown. Table 1 summarizes the thick waveguide samples essentially for 10.6-μm wavelength work. The carrier concentrations of these GaAs films are determined by the capacitance-voltage measurements and are typically in the mid 10^{13} per cm^3 range. Table 2 summarizes the thin waveguide samples essentially for one-micron wavelength work. For these thinner waveguides, the carrier concentrations are in the low $10^{14} cm^{-3}$ range, which is higher as expected.

2.3 $GaAs_{1-x}P_x/GaAs/GaAs_{1-x}P_x$ Waveguides

This sandwiched waveguide is required for our electro-optic modulator. Its configuration is similar to Figure 1 except with an additional layer of GaAsP on top of GaAs. Several samples have been grown and are listed in Table 3. They have good surface quality.

2.4 Surface Alloy Uniformity of GaAsP

The surface alloy uniformity of GaAsP will assure the surface uniformity in the refractive index, which is important in determining the waveguide properties, both theoretically and experimentally. The alloy composition is determined by the photoluminescence technique. A waveguide sample without GaAs film is used for this measurement. The sample has an area of 4 cm x 4 cm. Five points on the sample are used for the photoluminescence measurement. Figure 2 shows graphically the composition variation within the wafer. It is readily seen that the surface alloy uniformity is excellent and the variation is less than 1%.

2.5 Epitaxial Wafer Size

The GaAs/GaAsP waveguide structure has been successfully grown on wafers with maximum dimensions on the order of 7 cm. Epitaxial wafers of this type with increased length are desirable in order to reduce the modulation drive power of the electro-optical modulators. Figure 3 shows a typical wafer size. This sample has an area of 7 cm x 5 cm. The reflection of the camera is also shown on the wafer surface.

<u>Table 1. Thick Undoped GaAs/GaAsP waveguides</u>

Sample No.	Layer thickness, μm GaAs	GaAsP	Grade	N_{GaAs} $10^{13}cm^{-3}$	N_{GaAsP} $10^{16}cm^{-3}$
6-33	5.8	33	30	5.4	2.6
6-35	7.8	29	33	3	1.4
6-37	6.8	30	29	8	2.7
6-39	9.8	30	34	4	2.5
6-42	4.9	30	34	3.6	1.5
6-44	7.8	41	40	4.3	
6-47	13.7	36	34	3.7	
6-54	11.7	14	29	1.5	
6-76	9.6	45	47	2.7	0.6
6-78	7.8	41	41	2.7	1
6-92	5.9	41	57	4.5	1.4
6-94	9.7	43	49	95	0.6
6-96	7.8	45	41	233	1.7
6-98	9.8	44	44	4.3	1.3
6-115	4	45	47	4.8	0.9
6-122	22	39	42	16	0.9
6-124	5.8	64	42	6.4	0.9
6-133	6	41	41	4.2	1.1
6-135	4	39	45	4.7	0.5
6-138	10	39	43	1.1	0.6
6-147	5	45	41	6.7	0.7
6-149	4	35	37	5.6	1.3
6-151	6	32	39	4.6	0.6
6-154A	4	41	47	4.8	0.5
6-154B	4	41	47	7.6	2.1
6-156	49	71	44	3.9	2.3
6-158	44	74	49	0.1	1.6

Table 2. Thin Undoped GaAs/GaAsP waveguides

Sample No.	Layer thickness, μm			N_{GaAs}	N_{GaAsP}
	GaAs	GaAsP	Grade	$10^{14} cm^{-3}$	$10^{16} cm^{-3}$
6-57	2.0	30	30	4.7	3
6-59	1.5	27	24	4	3.2
6-66	1.4	27	35	15	5.1
6-80	2.0	45	41	2.7	1.3
6-90	2.5	45	51	1.4	1.3
6-106	2.0	39	43	1.5	0.5
6-111	2.9	45	49	0.8	0.3
6-126	1.5	43	43	3.4	1.1
6-129	1.2	44	44	4	0.9
6-131	1.0	41	42	3.9	1.1

Table 3. Sandwiched Undoped GaAsP/GaAs/GaAsP waveguides

Sample No.	Layer thickness, μm				N_{GaAs}	N_{GaAsP}
	GaAsP	GaAs	GaAsP	Grade	$10^{13} cm^{-3}$	$10^{16} cm^{-3}$
6-109	10	8	35	41		1.1
6-118	11.5	6	42	44		0.3
6-143	5	5	39	39		0.8

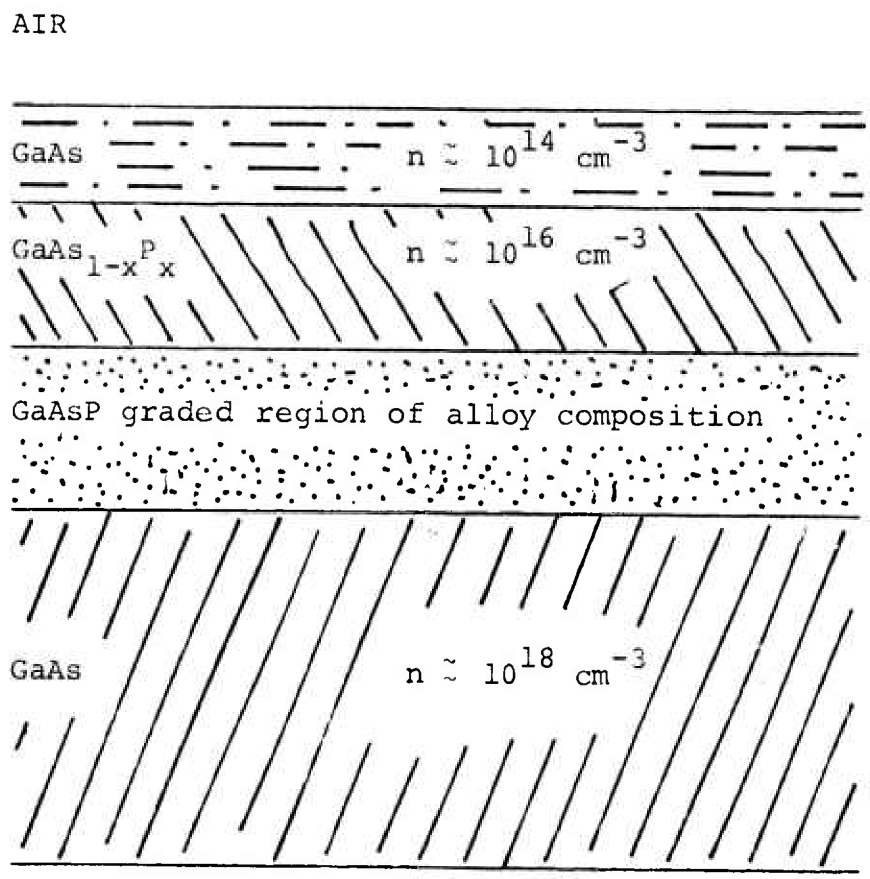

Figure 1: GaAs/GaAsP Waveguide Configuration

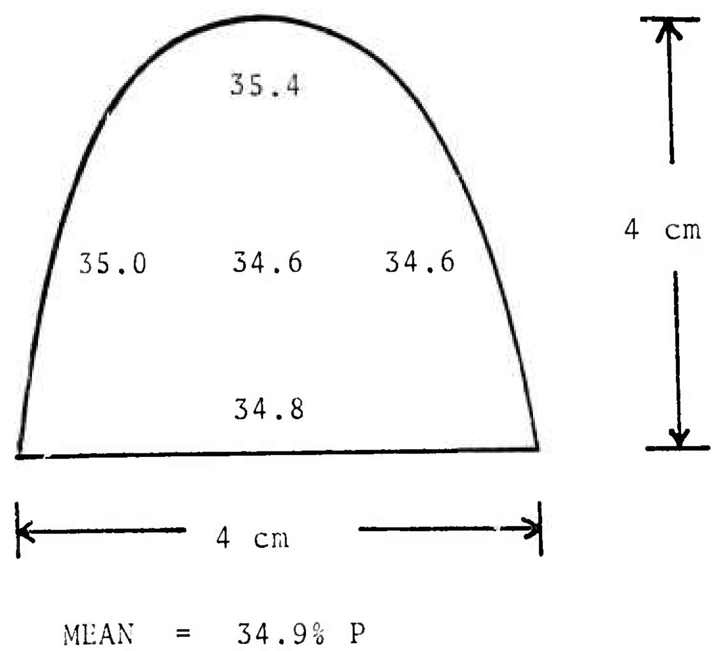

Figure 2: Surface Alloy Uniformity of GaAsP. Composition at five points showing degree of homogeneity.

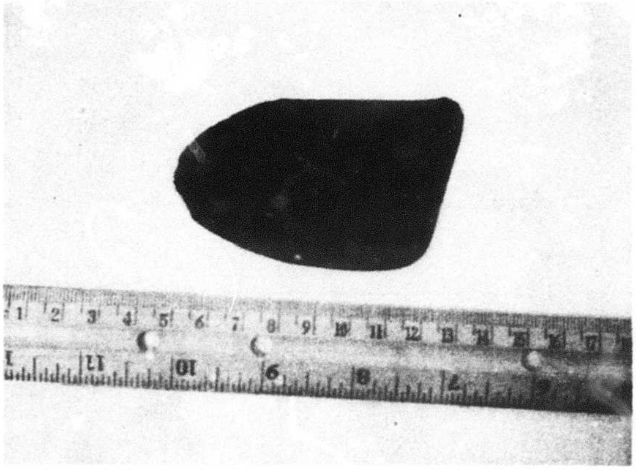

Figure 3: A typical wafer size. This sample has an area of 7 cm x 5 cm. The reflection of the camera is also shown on the wafer surface.

3. WAVEGUIDE EVALUATION

3.1 Introduction

Waveguide evaluation work has been concentrated at 10.6 μm wavelength in our early semi-annual reports. During this reporting period, we have initiated our waveguide evaluation work at one-micron wavelength, where the capabilities of low-loss optical fibers can best be used.

3.2 10.6 μm Wavelength

3.2.1 Loss Calculation in GaAs/GaAsP Waveguide Structure

The epi-layer GaAs has a carrier concentration of $10^{14}cm^{-3}$, while the GaAsP substrate has $10^{16}cm^{-3}$. The free carrier absorption in GaAs films is negligible as compared in the GaAsP substrate. The waveguide loss arises from the exponential tail of the guided mode in the film extending into the lossy substrate. We account for the loss in the substrate by expressing the refractive index of the substrate as a complex number:

$$\tilde{n}_0 = n_0 - iK_e = \sqrt{\varepsilon_r - i\frac{\sigma}{\omega\varepsilon_0}} \qquad (1)$$

Where ε_r is the relative dielectric constant of the substrate at the optical frequency, ε_0 is the permittivity of free space, σ is the conductivity of the substrate at the optical frequency, and ω is the angular frequency of the radiation. The propagation constant of the guided wave in this structure then becomes complex which results in an attenuation constant of the wave in the waveguide. One expects the effect of loss in the phase constant to be of second order. We assert that the presence of the free carriers in the substrate attenuates the waveguide mode without perturbing its propagation constant β. The wave velocity of a guided mode varies with small increment in n_0 for TE waves as:[1.]

$$\left(\frac{\Delta\beta}{K\Delta n_0}\right) = \frac{Kn_0}{\beta}\left[\frac{\dfrac{b_1^2}{p_0(p_0^2 + b_1^2)}}{W + \dfrac{1}{p_0} + \dfrac{1}{p_2}}\right] \qquad (2)$$

where

$$b_1^2 = K^2 n_1^2 - \beta^2$$

$$p_0^2 = \beta^2 - K^2 n_0^2$$

$$p_2^2 = \beta^2 - K^2 n_2^2$$

where W is the film thickness, β is the propagation constant and K is the free space wave number. Since we have expressed the substrate refractive index as complex $\tilde{n}_0 = n_0 + \Delta n_0 = n_0 - iK_e$, which then leads to the complex propagation constant $\tilde{\beta} = \beta + \Delta\beta = \beta - i\beta'$ by Equation (2), resulting in a loss coefficient of a guided wave

$$\alpha_N = 2\beta' = 2\Delta\beta \qquad (3)$$

Thus, Equation (2) has the physical meaning that the ratio $(\frac{\Delta\beta}{K\Delta n_0})$ a dimensionless number compares the loss in the film to the loss of plane wave propagation in the lossy substrate. Since β, b_1, p_0 and p_2 are all positive in Equation (2), the possible values of β/K range from n_0 to n_1. At the upper limit $\beta/K \rightarrow n_1$, we have $b_1 \rightarrow 0$. Equation (2) approaches zero. This is understandable since in this case the wave propagates as a plane wave in the GaAs film; the film thickness $W \to \infty$, and we have assumed the GaAs film to be lossless. At the lower limit, $\beta/K \to n_0$, $p_0 \to 0$, then Equation (2) becomes unity. This is readily understood since for a guided mode near cutoff, the electric field is mainly in the substrate; hence the loss of the guided wave approaches the bulk loss of the substrate. The loss ratio of Equation (3) has a value ranging from unity to zero.

3.2.2 Measurement of the Attenuation Rate in GaAs/GaAsP Waveguides

The GaAs/GaAsP waveguide has a configuration shown in Figure 1. The early GaAs/GaAsP waveguides had a bowed surface which prevented efficient light coupling and produced unreliable attenuation rate measurement. Improvement has been made by the modification in the graded region and flat waveguide structures have been obtained. Attenuation measurements have been performed on a number of GaAs/GaAsP samples. The measured data are plotted in Figure 4 We define the waveguide modes as the modes guided by the GaAs film. There are also composite waveguide modes since both GaAs and GaAsP layers are grown on a low index substrate of n^+GaAs. However, these composite waveguide modes have higher loss and are of no interest in device consideration. For a single mode waveguide, an attenuation rate of 2 dB/cm has been obtained. For a two-mode waveguide, an attenuation rate as low as 1.5 dB/cm for the fundamental mode has been obtained. It is our understanding that we have the lowest loss in a single mode waveguide at 10.6μm wavelength. Also shown in Figure 4 is the theoretical curve of loss. Equation (2) is evaluated with the following parameters: $n_0 = 3.12$, $n_1 = 3.275$ and $n_2 = 1.0$ at $\lambda = 10.6\mu m$. The propagation constant β is obtained by solving the waveguide mode equation. In the calculation, we have assumed a bulk loss of 10 dB/cm or 2.5 cm^{-1} for the GaAsP substrate at 10.6μm wavelength. This assumption should be valid because it agrees well with the results reported by Mil'vidskki et al[2] for the corresponding carrier concentrations in n-type gallium arsenide single crystals. The experimental points in Figure 4 lie above the theoretical curves. This can be understood since we have not included the film surface scattering loss and the film bulk loss in our theoretical calculation. Waveguides with loss less than 1 dB/cm can be fabricated by increasing the GaAs film thickness. For a 22-μm waveguide, the loss for the fundamental mode is so small that it is immeasureable. Because of the inaccuracy in our measurement, we are only able to say that the loss is less than 1 dB/cm. However, a multi-mode waveguide is undesirable from the device consideration.

A paper entitled "Low-Loss Large-Area GaAs/GaAsP Heterostructure as Optical Waveguide at 10.6 μm" has been presented at the <u>DOD/Industry-Wide Integrated Optics and Fiber Optics Communications Conference</u>, San Diego, 15-17 May, 1974. A written paper on the same subject has been published in <u>Optics Communications</u>, Vol. 11, pp. 201-203, June, 1974.

3.2.3 Measurement of the Attenuation Rate in GaAs/AlGaAs Waveguide

Toward the end of the last reporting period, one sample of GaAs/AlGaAs was made available for attenuation measurement. Over a length of about 5 mm, an attenuation rate of 3 dB/cm for TE_0 mode and 5 dB/cm for TE_1 mode were measured, with a GaAs film thickness about 8 μm. The sample size is small. Neverless, the measured attenuation rate is encouraging and is comparable with GaAs/GaAsP waveguides. As explained in our last semi-annual report, the liquid phase epitaxy of this program has been indefinitely suspended, no more samples of GaAs/AlGaAs waveguides were fabricated and no new results were obtained from the waveguide attenuation measurements.

3.2.4 Measurement of the Attenuation Rate in GaAsP/GaAs/GaAsP Waveguide

Many device designs call for an electrode layer on top of the waveguide layer. This metal layer causes tremendous loss to the optical signal in the waveguide. A way to reduce this metallic loss is to include a buffer layer between the waveguide layer and the metal layer. The buffer layer should be thick enough so that the exponential tail of the guided mode does not penetrate into the metal layer. In our waveguide structure the buffer layer is a thin layer of GaAsP on top of the GaAs waveguide. A sample has been fabricated with a 5μm GaAs waveguide, plus an additional layer of 5μm GaAsP as the buffer layer. Waveguide mode excitation is again achieved by using the germanium prism. The light coupling efficiency is low because of the longer optical tunneling region which now is composed of the air and the GaAsP buffer layer. Waveguide attenuation measurement is performed on this single-mode GaAsP/GaAs/GaAsP sandwich structure, and a very encouraging result of 6 dB/cm loss is obtained. The loss is mainly due to the free carrier absorption in the GaAsP substrate and the GaAsP buffer layer. Both have a carrier concentration of $10^{16} cm^{-3}$ which corresponds to a 10 dB/cm bulk loss at 10.6μm wavelength as explained earlier.

One way to reduce the waveguide attenuation loss is to reduce the free carrier concentration in the GaAsP layers.

3.2.5 Two-dimensional Waveguide Evaluation

A written paper entitled "Low-Loss Two-Dimensional GaAs Epitaxial Waveguides at 10.6 μm Wavelength" has been accepted for publication and appears in Transaction on Microwave Theory and Techniques, Vol. MTT-22, June, 1974. We have initiated a sputter etching process (the earlier work is by chemical etching) to fabricate two-dimensional waveguides. Our initial results indicate that we have a sharp edge definition of the order of 1 μm for a 50-μm wide guide.

3.2.6 Refractive Index Study of GaAsP

A literature survey[3] indicates that there are no published data on the refractive index of GaAsP at 10.6 μm wavlength. A rough way to estimate the refractive index of GaAsP is to determine the number of waveguide modes for a known film thickness. The minimum film thickness required to support a waveguide mode is given by[4]

$$W_{min} = \frac{1}{K(n_1^2 - n_0^2)^{1/2}} \left[m\pi + \tan^{-1}\left(\frac{n_0^2 - n_2^2}{n_1^2 - n_0^2}\right)^{1/2}\right] \quad (4)$$

where m is the mode order, K the free space wave number, $n_1 = 3.27$ for GaAs film, $n_2 = 1.0$ for air, and n_0 is the unknown. Figure 5 is a plot of W_{min} vs. n_0 by evaluating Equation (4). The waveguide thickness is conveniently measured microscopically. Several waveguides are used to excite the guided modes. Experimentally, a 7-μm thick waveguide supports only one guided mode, and Figure 5 indicates n_0 should be larger than 3.10. An 8-μm thick waveguide supports two guided modes, and Figure 5 indicates n_0 should be smaller than 3.14. Now, we roughly know $3.10 < n_0 < 3.14$ with the understanding that there is also error in film thickness measurement. We simply take the mean for $n_{GaAs_{1-x}P_x} = 3.12$ and $X = 0.35$ from the photoluminescence measurement. If we assume a linear depression Δn of the refractive index of $GaAs_{1-x}P_x$ from $n_{GaAs} = 3.27$ as a function of phosphorus content X, we obtain

$$\Delta n = -0.44X \text{ at } \lambda = 10.6\ \mu m \qquad (5)$$

The refractive index of $GaAs_{1-x}P_x$ has been calculated[5] based on the published[6] infrared reflectivity spectrum of $GaAs_{1-x}P_x$. Figure 6 shows the calculated dispersion curves of GaAs, $GaAs_{0.65}P_{0.35}$ and GaP. At $\lambda = 10.6\ \mu m$, the refractive index of $GaAs_{1-x}P_x$ as a function of X is shown in Figure 7. We obtain a linear approximation for $GaAs_{1-x}P_x$ as

$$\Delta n = -0.42X \text{ at } \lambda = 10.6\ \mu m \qquad (6)$$

Our rough estimate of Equation (5) agrees reasonably well with Equation (6). A more detailed experimental measurement is under way to determine the refractive index of $GaAs_{1-x}P_x$ at $\lambda = 10.6\ \mu m$.

3.3 1.06 μm Wavelength

3.3.1 Waveguide Mode Excitation

The evaluation of the waveguide at $\lambda = 1.06\ \mu m$ (also at $\lambda = 1.15\ \mu m$) has been initiated. Excitation of the waveguide modes has been achieved by several means. The GaAs/GaAsP waveguide structures shown in Figure 1 are used in this study. As the optical wavelength is decreased 10 times from 10.6 μm to 1.06 μm, the film thickness required is also decreased, accordingly. We are essentially dealing with waveguides of 1 - 2 μm thick. The edge illumination through the cleaved edge of the waveguide structure is successful, but with poor efficiency. Since the film thickness is on the order of wavelength, there is tremendous scattering loss due to the geometric mismatch between the light beam width of the film edge.

The photoresist grating coupler has been successfully fabricated to excite waveguide modes at 1.06 μm wavelength. The GaAs waveguide is coated with Shipley 1350 photoresist and is exposed to an interference pattern of two beams from an argon laser at 4880Å. The grating coupler has a periodicity of about 3700Å. Waveguide modes can selectively be coupled in and out of the film. This offers a convenient way to determine the propagation constants of each mode in the waveguide, which supply enough information to calculate the refractive indices of the waveguide structure. Our initial results give a reliable index data up to second decimal point. Improvements are needed to get better accuracy.

A prism film coupler is not readily available for GaAs waveguide at 1.06 μm wavelength. The reason is that GaAs has such high index, $n_{GaAs} = 3.48$. We have not been able to find a material higher in index, but also transparent at 1.06 μm. We have fabricated a GaAs prism. It has a carrier concentration of $7 \times 10^{16} cm^{-3}$, while the GaAs film is in the range of $10^{14} cm^{-3}$. The index variation caused by the free carrier concentration at the levels of our prism and film is negligible[3] at 1.06 μm. We assume equal index for our prism and film. The prism is fabricated with a base angle of 85°. Waveguide modes are observed with this prism as an output coupler. However, we anticipate difficulty in exciting the fundamental waveguide mode with this prism.

Guiding of 1.06 μm radiation in GaAs/GaAsP waveguide has been observed. No quantitative attenuation measurement has been made yet, but qualitatively, the results appear encouraging. With the success of the GaAs prism coupler, we are in the process to measure the attenuation, at least of the higher order modes.

3.3.2 Thin-film Laser Coupling Into a Passive Waveguide

This project is not supported by this contract. We have included this in the report because of its relevant importance in our one micron work.

A practical integrated optical circuit requires a thin-film laser source coupled to a waveguide for modulation or switching. The interconnection has been suggested in the form of a block coupler[7]. It is essentially a thin-film laser source put face to face to a waveguide. Light coupling occurs through the evanescent field in the air gap. We have demonstrated the feasibility of this approach by using a thin-film dye laser. A rhodamine 6G doped polyurethane film is transversely pumped with a N_2 laser. The laser emits a broadband signal of about 200Å bandwidth centered at about 6000Å. When a sputtered glass waveguide is clamped to the thin-film dye laser in the block coupling configuration, the dye laser signal is coupled to the glass waveguide. The output spectrum from the glass waveguide resembles closely the thin-film dye laser spectrum. There is no appreciable change in the half-power bandwidth before and after coupling. This experiment demonstrates that the block coupler scheme is feasible to couple in $In_xGa_{1-x}As$ laser[8] at 1.06 μm to our GaAs/GaAsP waveguide structure. This particular combination offers a practical integrated optical communication system to be realized in the near future.

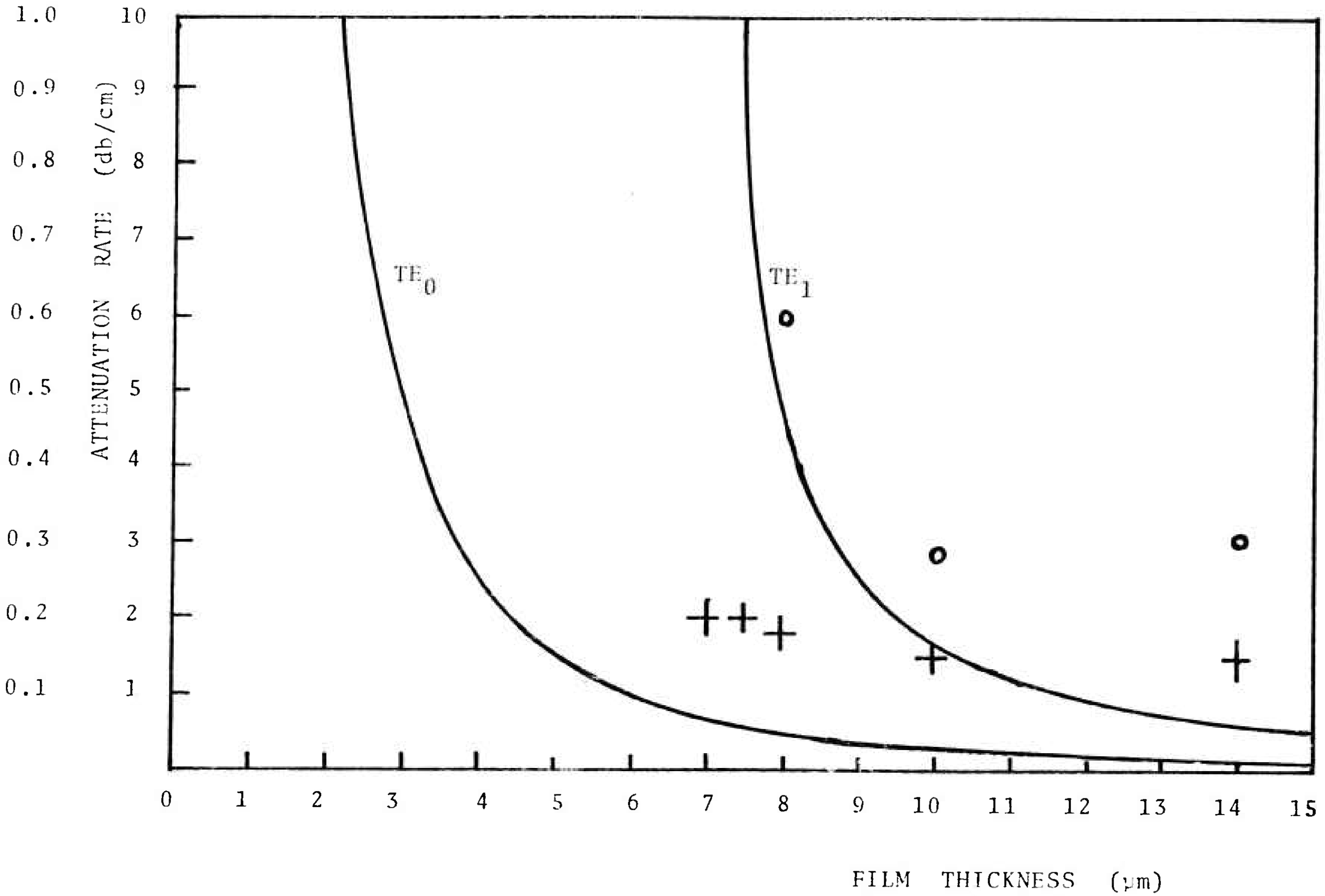

Figure 4: Attenuation rate of GaAs/GaAsP waveguide. Solid lines are the theoretical curves. Crosses are for TE_0 modes and circles are for TE_0 modes.

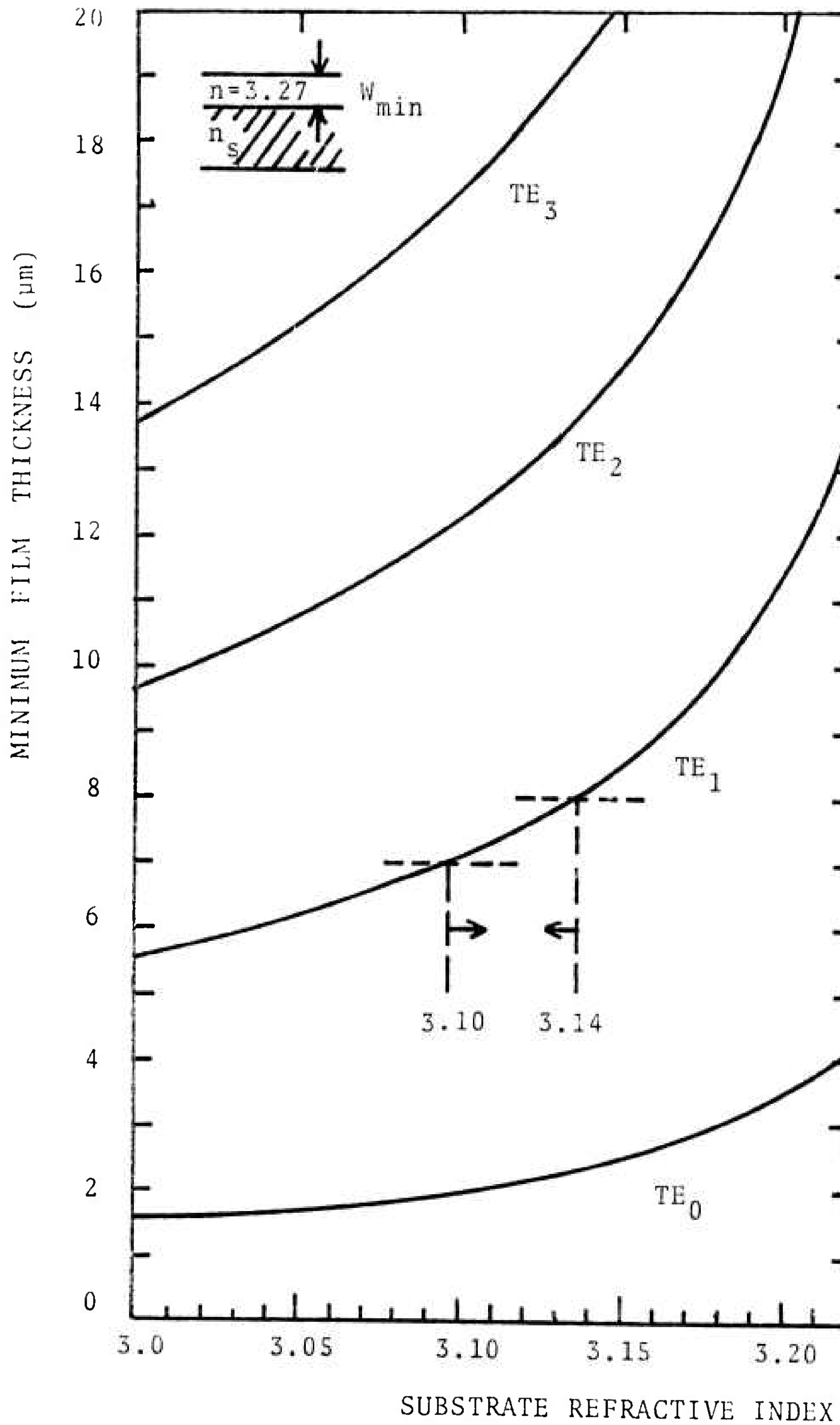

Figure 5: Minimum film thickness vs. substrate refractive index.

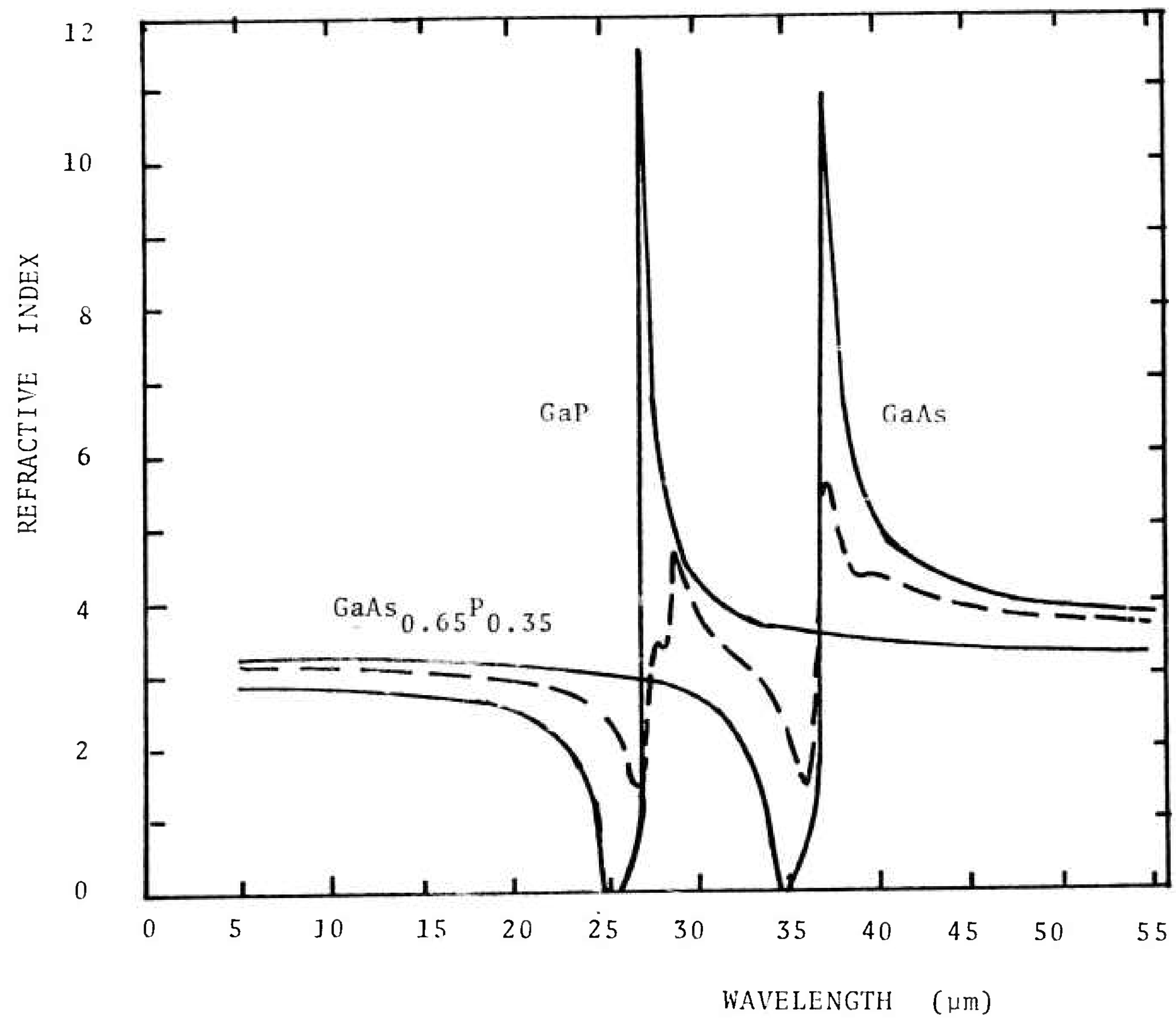

Figure 6: Refractive indices of GaAs, $GaAs_{0.65}P_{0.35}$ and GaP as a function of wavelength.

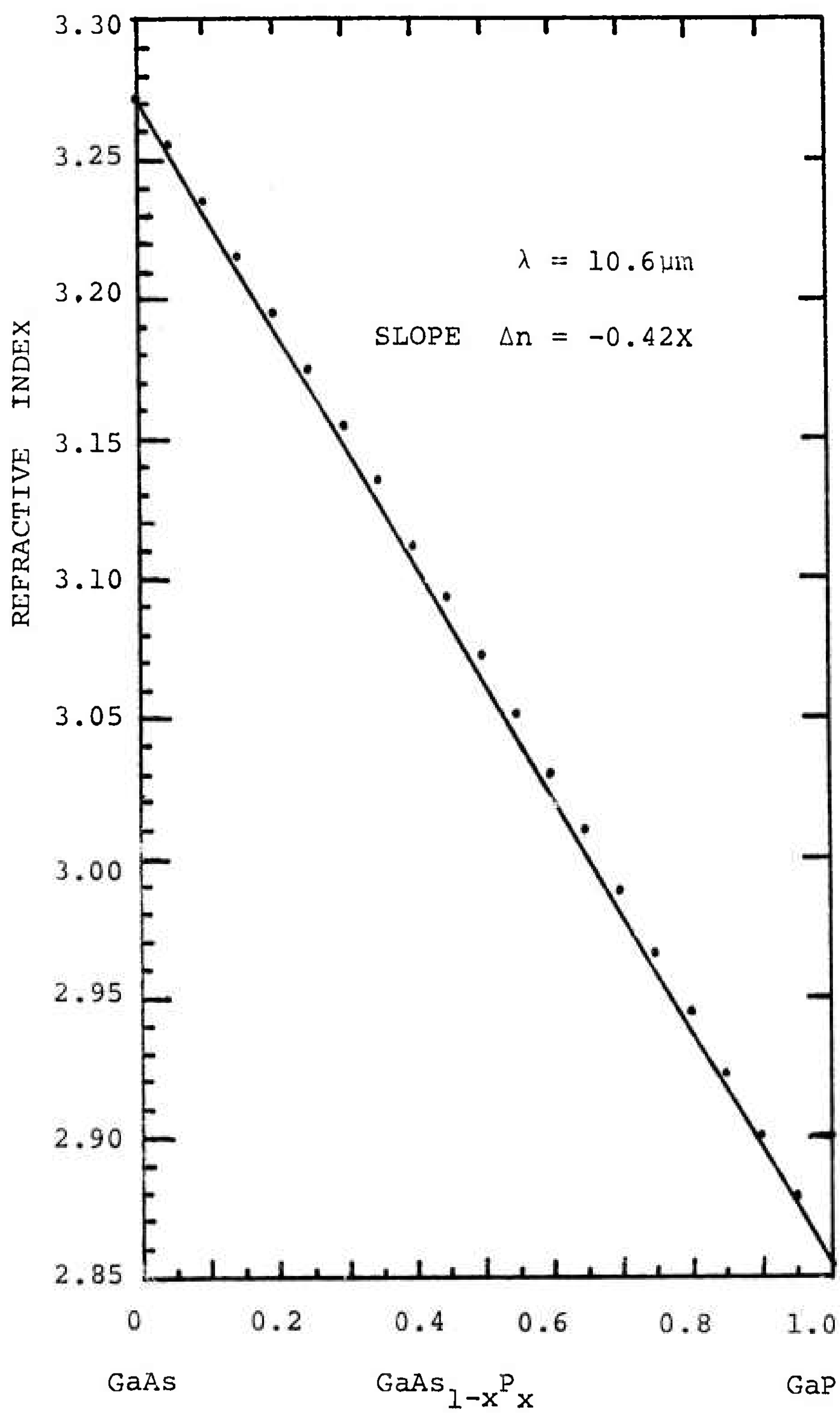

Figure 7: Refractive index of $GaAs_{1-x}P_x$ at 10.6 μm as a function of phosphorus content.

4. WORK FOR NEXT PERIOD

4.1 Materials Growth

Continue work on GaAs/GaAsP waveguides.

Improve GaAsP/GaAs/GaAsP waveguides.

Study the alloy composition of GaAs/GaAsP waveguide as a function of film depth.

4.2 Waveguide Evaluation

Evaluate new GaAs/GaAsP waveguides at $\lambda = 10.6$ μm.

Evaluate new GaAsP/GaAs/GaAsP waveguides at $\lambda = 10.6$ μm.

Evaluate proton implanted GaAs/n^+GaAs waveguides in collaboration with AFCRL.

Evaluate neutron irradiated and gamma irradiated GaAs/n^+GaAs and GaAs/GaAsP waveguides in collaboration with Harry Diamond Laboratory.

Fabricate and evaluate electro-optic modulator with GaAs/GaAsP waveguide.

Fabricate and evaluate electro-optic modulator with GaAsP/GaAs/GaAsP waveguides.

Measure the refractive index of $GaAs_{1-x}P_x$ at 10.6 μm.

Fabricate and evaluate a p-n junction in GaAsP/GaAs/GaAsP waveguides.

Fabricate and evaluate two-dimensional GaAs/GaAsP and GaAsP/GaAs/GaAsP waveguides at 10.6 μm.

Evaluate GaAs/GaAsP waveguides at $\lambda = 1.06$ μm and $\lambda = 1.15$ μm.

Fabricate grating couplers on GaAs/GaAsP waveguides for $\lambda = 1.06$ μm and $\lambda = 1.15$ μm.

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